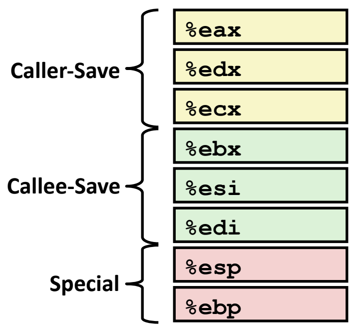
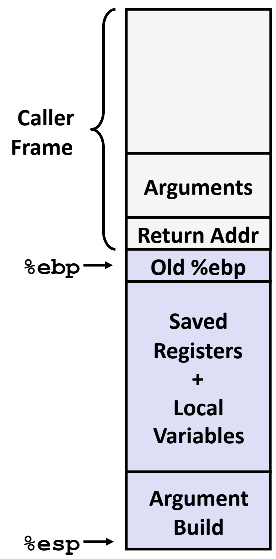
Last Time

- **Procedures (IA32)**
  - call / return
  - %esp, %ebp
  - local variables
  - recursive functions





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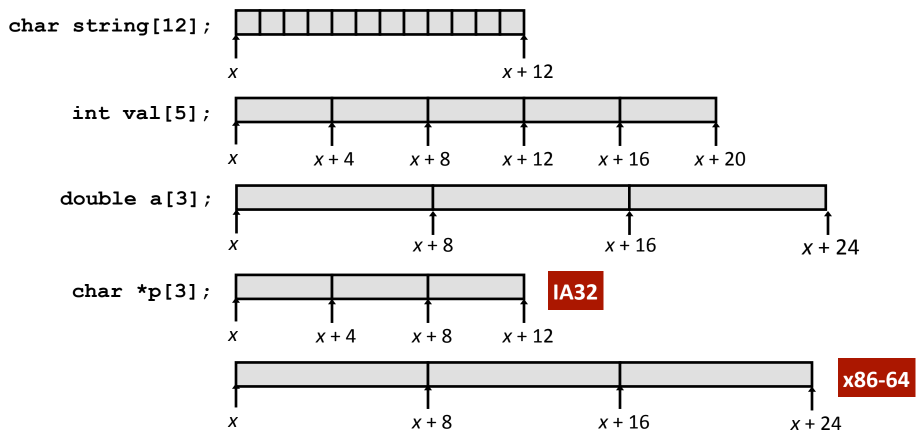
Today

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structs**
  - Alignment
- **Unions**

Array Allocation

- **Basic Principle**

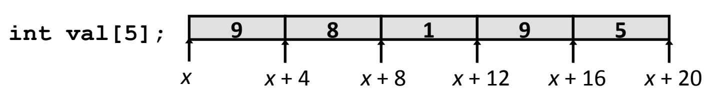
  T **A**[*N*];
  - Array of data type *T* and length *N*
  - Contiguously allocated region of *N* * **sizeof**(*T*) bytes



Array Access

- **Basic Principle**

  T **A**[*N*];
  - Array of data type *T* and length *N*
  - Identifier **A** can be used as a pointer to array element 0: Type *T**

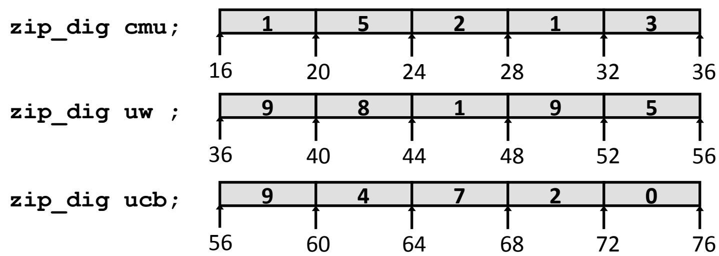


Reference	Type	Value
`val[4]`	`int`	5
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	8
`val + i`	`int *`	*x* + 4 *i*

Array Example

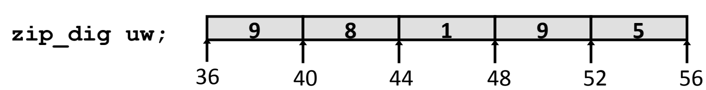
```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



- **Declaration "`zip_dig uw`" equivalent to "`int uw[5]`"**
- **Example arrays were allocated in successive 20 byte blocks**
  - Not guaranteed to happen in general

Array Accessing Example



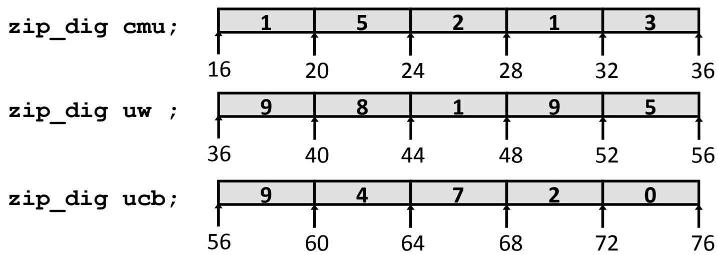

```
int get_digit
  (zip_dig z, int dig)
{
  return z[dig];
}
```

IA32

```
# %edx = z
# %eax = dig
movl (%edx,%eax,4),%eax   # z[dig]
```

- **Register `%edx` contains starting address of array**
- **Register `%eax` contains array index**
- **Desired digit at `4*%eax + %edx`**
- **Use memory reference `(%edx,%eax,4)`**

Referencing Examples

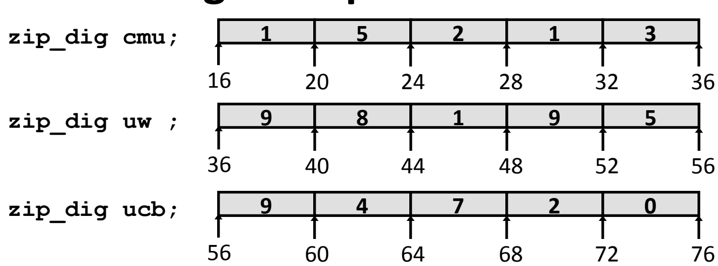


- **Reference** **Address** **Value** **Guaranteed?**

  `uw[3]`
  `uw[6]`
  `uw[-1]`
  `cmu[15]`

  What are these values?

Referencing Examples



Reference	Address	Value	Guaranteed?
`uw[3]`	`36 + 4* 3 = 48`	`9`	Yes
`uw[6]`	`36 + 4* 6 = 60`	`4`	No
`uw[-1]`	`36 + 4*-1 = 32`	`3`	No
`cmu[15]`	`16 + 4*15 = 76`	`??`	No

- No bound checking
- Out-of-range behavior implementation-dependent
- No guaranteed relative allocation of different arrays

Array Loop Example

- **Original**

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

- **Transformed**
  - As generated by GCC
  - Eliminate loop variable `i`
  - Convert array code to pointer code
  - Express in do-while form (no test at entrance)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z <= zend);
  return zi;
}
```


Array Loop Implementation (IA32)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %ecx = z
  xorl %eax,%eax
  leal 16(%ecx),%ebx
.L59:
  leal (%eax,%eax,4),%edx
  movl (%ecx),%eax
  addl $4,%ecx
  leal (%eax,%edx,2),%eax
  cmpl %ebx,%ecx
  jle .L59
```

Translation?

Array Loop Implementation (IA32)

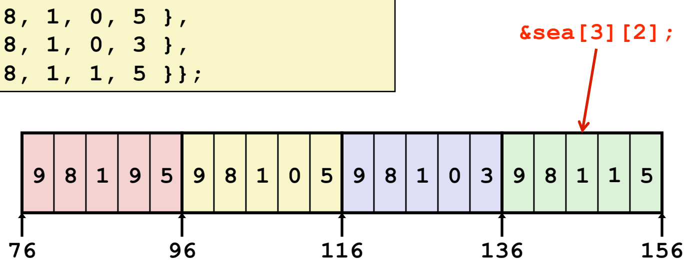
- **Registers**
  - `%ecx z`
  - `%eax zi`
  - `%ebx zend`
- **Computations**
  - `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
  - `z++` increments by 4

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %ecx = z
  xorl %eax,%eax             # zi = 0
  leal 16(%ecx),%ebx         # zend  = z+4
.L59:
  leal (%eax,%eax,4),%edx  # 5*zi
  movl (%ecx),%eax           # *z
  addl $4,%ecx               # z++
  leal (%eax,%edx,2),%eax  # zi = *z + 2*(5*zi)
  cmpl %ebx,%ecx             # z : zend
  jle .L59                   # if <= goto loop
```


Nested Array Example

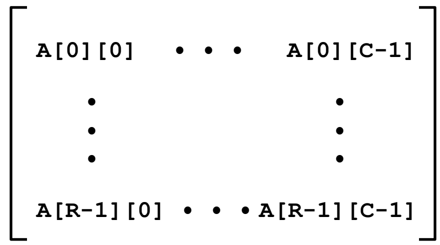
```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```



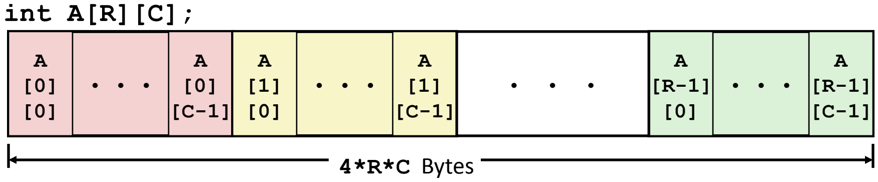
- **"`zip_dig sea[4]`" equivalent to "`int sea[4][5]`"**
  - Variable **`sea`**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **`int`**s, allocated contiguously
- **"row-major" ordering of all elements guaranteed**

Multidimensional (Nested) Arrays

- **Declaration**
  - *T* **A**[*R*][*C*];
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes
- **Array size**
  - *R* * *C* * *K* bytes
- **Arrangement**
  - Row-major ordering



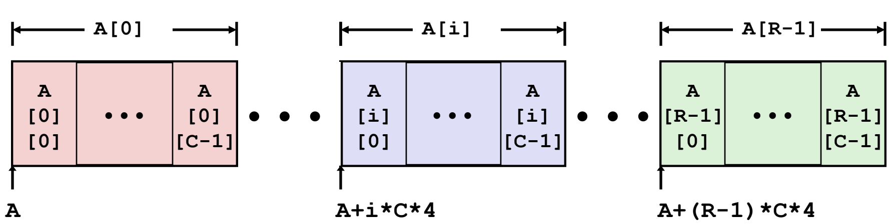
int A[R][C];



Nested Array Row Access

- **Row vectors**
  - **A[i]** is array of *C* elements
  - Each element of type *T* requires *K* bytes
  - Starting address **A +** *i* * (*C* * *K*)

int A[R][C];



Nested Array Row Access Code

```
int *get_sea_zip(int index)
{
  return sea[index];
}
```

```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

- What data type is `sea[index]`?
- What is its starting address?

```
  # %eax = index
   leal  (%eax,%eax,4),%eax
   leal  sea(,%eax,4),%eax
```

Translation?

Nested Array Row Access Code

```
int *get_sea_zip(int index)
{
  return sea[index];
}
```

```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

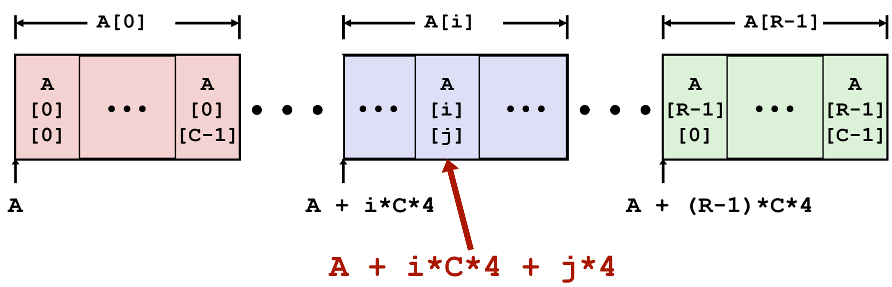
```
  # %eax = index
   leal  (%eax,%eax,4),%eax  # 5 * index
   leal  sea(,%eax,4),%eax   # sea + (20 * index)
```

- **Row Vector**
  - `sea[index]` is array of 5 `int`s
  - Starting address `sea+20*index`
- **IA32 Code**
  - Computes and returns address
  - Compute as `sea+4*(index+4*index)=sea+20*index`

Nested Array Row Access

- **Array Elements**
  - **`A[i][j]`** is element of type *T*, which requires *K* bytes
  - Address **`A +`** $i * (C * K) + j * K = A + (i * C + j) * K$

```
int A[R][C];
```



Nested Array Element Access Code

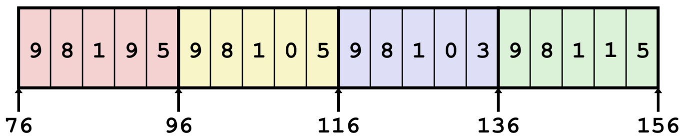
```
int get_sea_digit
  (int index, int dig)
{
  return sea[index][dig];
}
```

```
# %ecx = dig
# %eax = index
leal 0(,%ecx,4),%edx          # 4*dig
leal (%eax,%eax,4),%eax       # 5*index
movl sea(%edx,%eax,4),%eax    # *(sea + 4*dig + 20*index)
```

- **Array Elements**
  - **`sea[index][dig]`** is **`int`**
  - Address: **`sea + 20*index + 4*dig`**
- **IA32 Code**
  - Computes address **`sea + 4*dig + 4*(index+4*index)`**
  - **`movl`** performs memory reference

Strange Referencing Examples

```
zip_dig
sea[4];
```



- **Reference** **Address** **Value** **Guaranteed?**

  `sea[3][3]`
  `sea[2][5]`
  `sea[2][-1]`
  `sea[4][-1]`
  `sea[0][19]`
  `sea[0][-1]`

What are these values?

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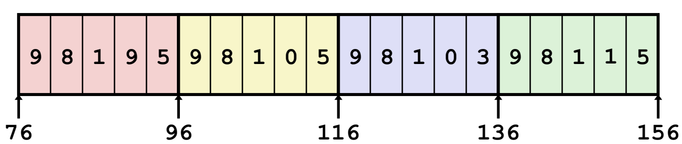
Strange Referencing Examples

```
zip_dig
sea[4];
```



Reference	Address	Value	Guaranteed?
`sea[3][3]`	`76+20*3+4*3 = 148`	2	Yes
`sea[2][5]`	`76+20*2+4*5 = 136`	1	Yes
`sea[2][-1]`	`76+20*2+4*-1 = 112`	3	Yes
`sea[4][-1]`	`76+20*4+4*-1 = 152`	1	Yes
`sea[0][19]`	`76+20*0+4*19 = 152`	1	Yes
`sea[0][-1]`	`76+20*0+4*-1 = 72`	??	No

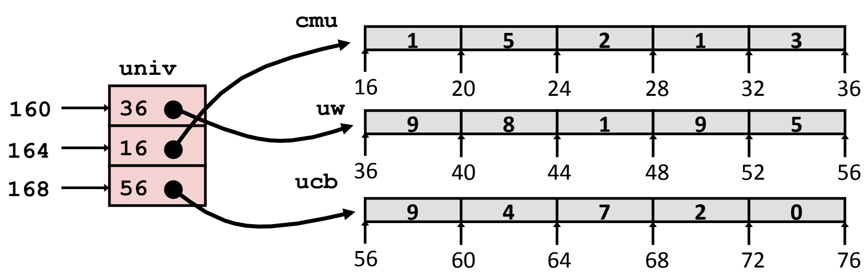
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

Multi-Level Array Example

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

```
#define UCOUNT 3
int *univ[UCOUNT] = {uw, cmu, ucb};
```

- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 4 bytes
- Each pointer points to array of `int`s



Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

```
  # %ecx = index
  # %eax = dig
  leal 0(,%ecx,4),%edx
  movl univ(%edx),%edx
  movl (%edx,%eax,4),%eax
```

Translation?

Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

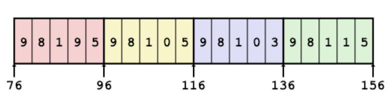
```
  # %ecx = index
  # %eax = dig
  leal 0(,%ecx,4),%edx     # 4*index
  movl univ(%edx),%edx     # Mem[univ+4*index]
  movl (%edx,%eax,4),%eax  # Mem[...+4*dig]
```

- **Computation (IA32)**
  - Element access `Mem[Mem[univ+4*index]+4*dig]`
  - Must do two memory reads
    - First get pointer to row array
    - Then access element within array

Array Element Accesses

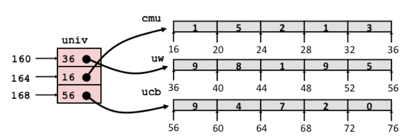
Nested array

```
int get_sea_digit
  (int index, int dig)
{
  return sea[index][dig];
}
```



Multi-level array

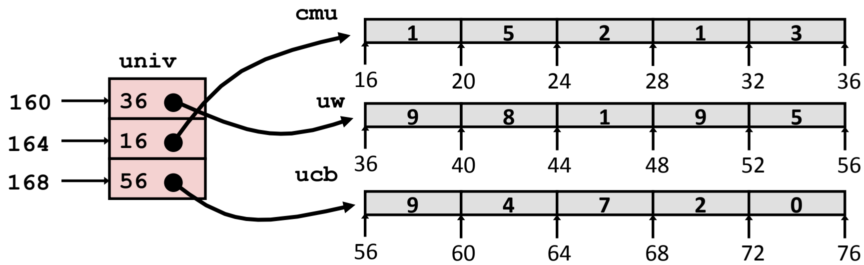
```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```



Access looks similar, but it isn't:

`Mem[sea+20*index+4*dig]`   `Mem[Mem[univ+4*index]+4*dig]`

Strange Referencing Examples



- **Reference** **Address** **Value** **Guaranteed?**
  - `univ[2][3]`
  - `univ[1][5]`
  - `univ[2][-1]`
  - `univ[3][-1]`
  - `univ[1][12]`

What values go here?

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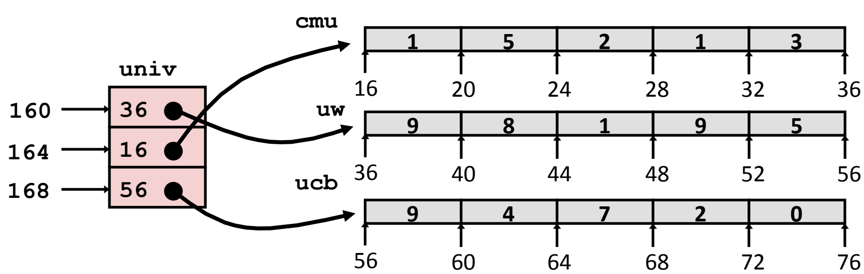
Strange Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`	`56+4*3 = 68`	2	Yes
`univ[1][5]`	`16+4*5 = 36`	9	No
`univ[2][-1]`	`56+4*-1 = 52`	5	No
`univ[3][-1]`	`??`	`??`	No
`univ[1][12]`	`16+4*12 = 64`	7	No

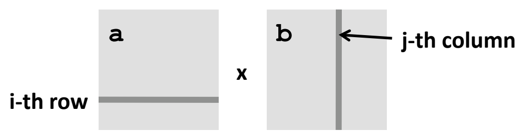
- Code does not do any bounds checking
- Ordering of elements in different arrays not guaranteed

Using Nested Arrays

- **Strengths**
  - C compiler handles doubly subscripted arrays
  - Generates very efficient code
  - Avoids multiply in index computation
- **Limitation**
  - Only works for fixed array size

```
#define N 16
typedef int fix_matrix[N][N];
```

```
/* Compute element i,k of
   fixed matrix product */
int fix_prod_ele
(fix_matrix a, fix_matrix b,
 int i, int k)
{
  int j;
  int result = 0;
  for (j = 0; j < N; j++)
    result += a[i][j]*b[j][k];
  return result;
}
```



Dynamic Nested Arrays

- **Strength**
  - Can create matrix of any size
- **Programming**
  - Must do index computation explicitly
- **Performance**
  - Accessing single element costly
  - Must do multiplication

```
int * new_var_matrix(int n)
{
  return (int *)
    calloc(sizeof(int), n*n);
}
```

```
int var_ele
  (int *a, int i, int j, int n)
{
  return a[i*n+j];
}
```

```
movl 12(%ebp),%eax        # i
movl 8(%ebp),%edx         # a
imull 20(%ebp),%eax       # n*i
addl 16(%ebp),%eax        # n*i+j
movl (%edx,%eax,4),%eax   # Mem[a+4*(i*n+j)]
```

Dynamic Array Multiplication

- **Without Optimizations**
  - Multiplies: 3
    - 2 for subscripts
    - 1 for data
  - Adds: 4
    - 2 for array indexing
    - 1 for loop index
    - 1 for data

```
/* Compute element i,k of
   variable matrix product */
int var_prod_ele
   (int *a, int *b,
    int i, int k, int n)
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result +=
      a[i*n + j] * b[j*n + k];
  return result;
}
```


Optimizing Dynamic Array Multiplication

- **Optimizations**
  - Performed when set optimization level to **-O2**
- **Code Motion**
  - Expression **i*n** can be computed outside loop
- **Strength Reduction**
  - Incrementing **j** has effect of incrementing **j*n+k** by **n**
- **Operations count**
  - 4 adds, 1 mult
- **Compiler can optimize regular access patterns**

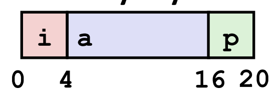
```
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result +=
      a[i*n + j] * b[j*n + k];
  return result;
}
```

```
{
  int j;
  int result = 0;
  int iTn = i*n;
  int jTnPk = k;
  for (j = 0; j < n; j++) {
    result +=
      a[iTn + j] * b[jTnPk];
    jTnPk += n;
  }
  return result;
}
```

Structures

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

Memory Layout



- **Concept**
  - Contiguously-allocated region of memory
  - Refer to members within structure by names
  - Members may be of different types
- **Accessing structure member**

```
void
set_i(struct rec *r,
      int val)
{
     r->i = val;
// (*r).i = val;
}
```

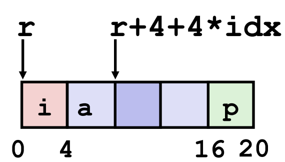
In java: r.i = val;

IA32 Assembly

```
# %eax = val
# %edx = r
movl %eax,(%edx)    # Mem[r] = val
```


Generating Pointer to Structure Member

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```



- **Generating Pointer to Array Element**
  - Offset of each structure member determined at compile time

```
int *find_a  //  r.a[idx]
 (struct rec *r, int idx)
{
   return &r->a[idx];
// return &(*((*r).a + idx));
}
```

In java? …

```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax   # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```

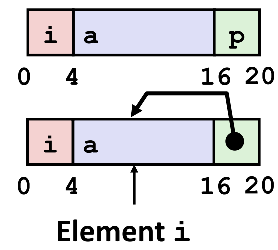
Structure Referencing (Cont.)

- **C Code**

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

```
void
set_p(struct rec *r)
{
     r->p = &r->a[r->i];
//  (*r).p = &(*((*r).a+(*r).i)));
}
```

```
 # %edx = r
 movl  (%edx),%ecx        # r->i
 leal  0(,%ecx,4),%eax    # 4*(r->i)
 leal  4(%edx,%eax),%eax  # r+4+4*(r->i)
 movl  %eax,16(%edx)      # Update r->p
```



In java? …

Alignment

- **Aligned Data**
  - Primitive data type requires K bytes
  - Address must be multiple of K
  - Required on some machines; advised on IA32
    - treated differently by IA32 Linux, x86-64 Linux, and Windows!
- **Motivation for Aligning Data**
  - Memory accessed by (aligned) chunks of 4 or 8 bytes (system-dependent)
    - Inefficient to load or store datum that spans quad word boundaries
    - Virtual memory very tricky when datum spans two pages (later…)
- **Compiler**
  - Inserts gaps in structure to ensure correct alignment of fields

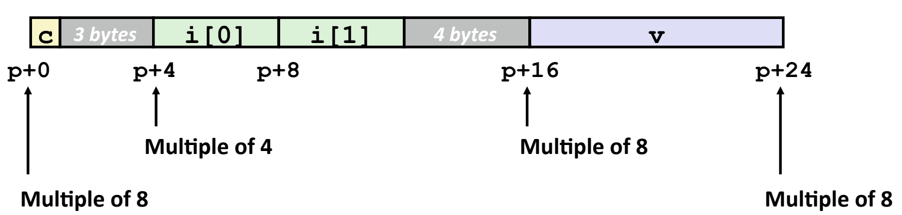
Specific Cases of Alignment (IA32)

- 1 byte: `char`, …
  - no restrictions on address
- 2 bytes: `short`, …
  - lowest 1 bit of address must be 0_2
- 4 bytes: `int`, `float`, `char *`, …
  - lowest 2 bits of address must be 00_2
- 8 bytes: `double`, …
  - Windows (and most other OS's & instruction sets): lowest 3 bits 000_2
  - Linux: lowest 2 bits of address must be 00_2
    - i.e., treated the same as a 4-byte primitive data type
- 12 bytes: `long double`
  - Windows, Linux: (same as Linux double)

Satisfying Alignment with Structures

- **Within structure:**
  - Must satisfy element's alignment requirement
- **Overall structure placement**
  - Each structure has alignment requirement K
    - K = Largest alignment of any element
  - Initial address & structure length must be multiples of K
- **Example (under Windows or x86-64):**
  - K = 8, due to `double` element

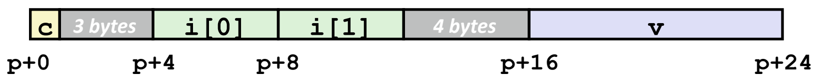
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



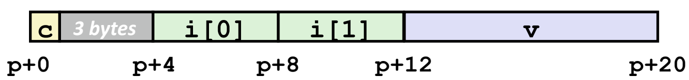
Different Alignment Conventions

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

- **IA32 Windows or x86-64:**
  - K = 8, due to **`double`** element



- **IA32 Linux**
  - K = 4; **`double`** treated like a 4-byte data type



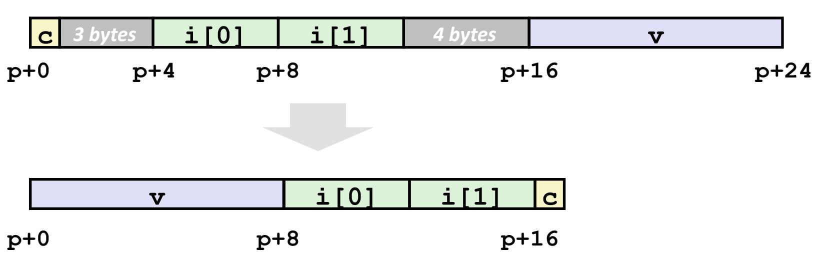
Saving Space

- **Put large data types first**

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```

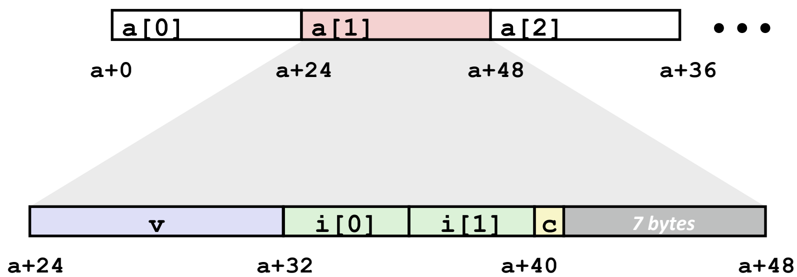
- **Effect (example x86-64, both have *K=8*)**



Arrays of Structures

- Satisfy alignment requirement for every element

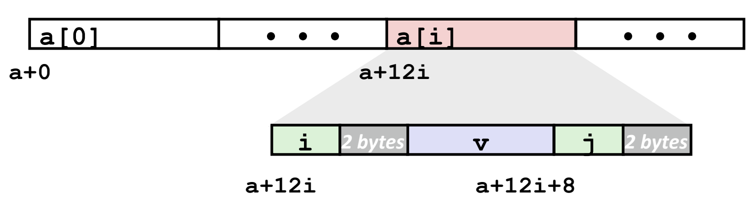
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```

- Compute array offset 12i
- Compute offset 8 with structure
- Assembler gives offset a+8
  - Resolved during linking




```
short get_j(int idx)
{
  return a[idx].j;
// return (a + idx)->j;
}
```

```
# %eax = idx
leal (%eax,%eax,2),%eax # 3*idx
movswl a+8(,%eax,4),%eax
```

Unions

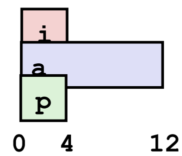
```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

```
union U1 {
  int i;
  int a[3];
  int *p;
} *up;
```

- **Concept**
  - Allow same regions of memory to be referenced as different types
  - Aliases for the same memory location

Structure Layout

Union Layout

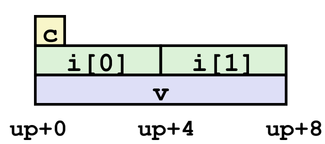


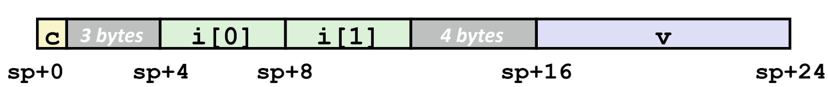
Union Allocation

- **Allocate according to largest element**
- **Can only use one field at a time**

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```

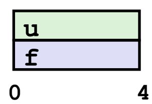
```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```





Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```




```
float bit2float(unsigned u)
{
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

Same as `(float) u` ?

Same as `(unsigned) f` ?

Summary

- **Arrays in C**
  - Contiguous allocation of memory
  - Aligned to satisfy every element’s alignment requirement
  - Pointer to first element
  - No bounds checking
- **Structures**
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- **Unions**
  - Overlay declarations
  - Way to circumvent type system